Thickness and shear-velocity mapping of Holocene-Pleistocene sediments by array studies of microtremors

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Principal Investigator: Dr Michael W Asten
School of Geosciences
Monash University
Melbourne VIC 3800 Australia
Tel +61 3 9905 1639 Fax +61 3 9905 4903
Email: michael.asten@sci.monash.edu.au
URL: http://www.earth.monash.edu.au

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BACKGROUND

Microtremors are seismic noise generated mainly by cultural sources (vehicles, machinery) in the frequency band of interest (1 to 30 Hz). Use of this "background noise" constitutes a "passive seismic" method. Microtremor methods are in wide use for purposes of site classification in earthquake seismic hazard studies. Single-station spectral methods (eg Nakamura,1989; Ibs von Seht and Wohlenburg, 1999) are now common around the world for gaining reconnaissance site-resonance information.

Array methods provide more advanced methodologies which measure surface-wave dispersion properties of the microtremors, and yield shear-velocity and thickness information. Such array methods fall into two classes, (a) beam-forming techniques, as used eg by Liu et al (2001), and (b) spatial autocorrelation (**SPAC**) methods. The latter are strictly applicable only to circular arrays, but have a powerful advantage in that they yield scalar wave velocity in the presence of omni-directional sesimic noise, and thus are especially applicable to the processing of microtremor data from multiple cultural sources. These SPAC techniques have been most highly developed in Japan (eg Aki, 1957, 1965; Okada, 1997; Kudo et al, 2002) but have also been developed and enhanced for multi-modal analysis by Asten (1976, 2001) and applied to microtremor studies in Australia in collaborative studies with Geoscience Australia (Asten and Dhu, 2002; Asten, Lam et al, 2002; Asten et al, 2003).

Dr Asten brings two novel contributions to the SPAC method as applied in this Project:

- Array design which has allowed extension of the SPAC concept to the simultaneous solution of two modes of Rayleigh-wave propagation of microtremors (Asten, 1976; 1978a; 2001), and
- Introduction of an algorithm (multi-mode SPAC or MMSPAC) for direct fitting of layered-earth parameters to azimuthally averaged coherencies (Asten, Lam, et al, 2002; Asten et al,

2004; Roberts and Asten, 2004) which provides improved stability of the inversion process, and facilitates identification of multiple modes of wave propagation.

INVESTIGATIONS UNDERTAKEN

There are four phases of work incorporated in this project:

1) Collaborate with USGS and other personnel in synthesis and publication of the various "blind" trials of active and passive seismic methods at the Coyote Creek site, Santa Clara Valley.
2) Improve the SPAC interpretation at Coyote Creek using the available multiple station separations.
3) Participate in array design and acquisition of four further data sets at sites in the Santa Clara Valley, being Guadalupe, Santana Park, Saratoga Park and McGlincey. Each of these sites has independent data available from a deep water bore and P-S wave borehole logging to a depth of order 300 m.
4) Develop a prototype inversion software for SPAC data operating on coherency spectra (as distinct from the conventional approach of inverting phase-velocity dispersion curves).

RESULTS

Collaboration in comparison of active and passive seismic methods at the Coyote Creek site

The results for Coyote Creek obtained in this project using MMSPAC were compared with eight other approaches, both active (seismic refraction, reflection, MASW, SASW) and passive (single-station HVSR, SPAC and F-K array beam-forming methods) at a workshop convened by Dr Dave Boore at Menlo Pk, May 3, 2004. The comparison is subject of a USGS Open File Report in preparation.

Improved SPAC interpretation at Coyote Creek

Microtremor data data acquired at Coyote Creek (Santa Clara Valley) by USGS and UNAM-Mexico in 2002 was reprocessed and interpreted using the MMSPAC method of direct matching of coherency spectra. Figure 1 shows the match of observed and model data for the layered-earth model of Figure 2. This interpretation was made "blind" ie without access to any independent geological or velocity data. Subsequent re-interpretation corrects the model by inserting a known basement at 1000 m, but interpreted Vs above 500 m is essentially unchanged. Figure 3 shows a comparison of the "blind" interpreted Vs profile with independently measured borehole velocity logs.

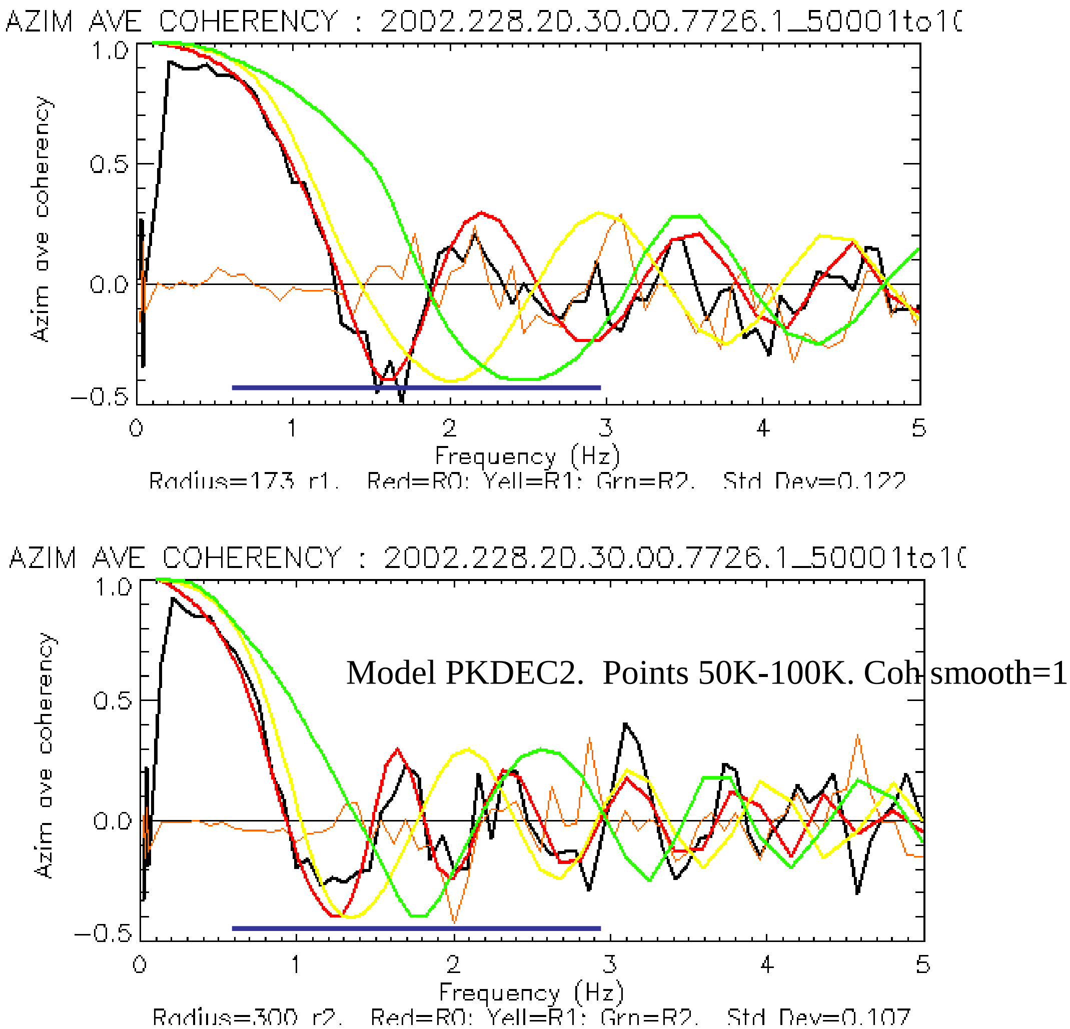


Fig.1. Interpretation of SPAC data for Coyote Creek for station spacings 173 m and 300 m (four-station triangular array). Black line: observed SPAC coherency spectra. Red: modelled fundamental-mode Rayleigh (R0) wave SPAC for a preferred layered-earth model. Yellow and green: modelled higher mode R1 and R2 SPAC for reference (not used in curve fitting in this example).

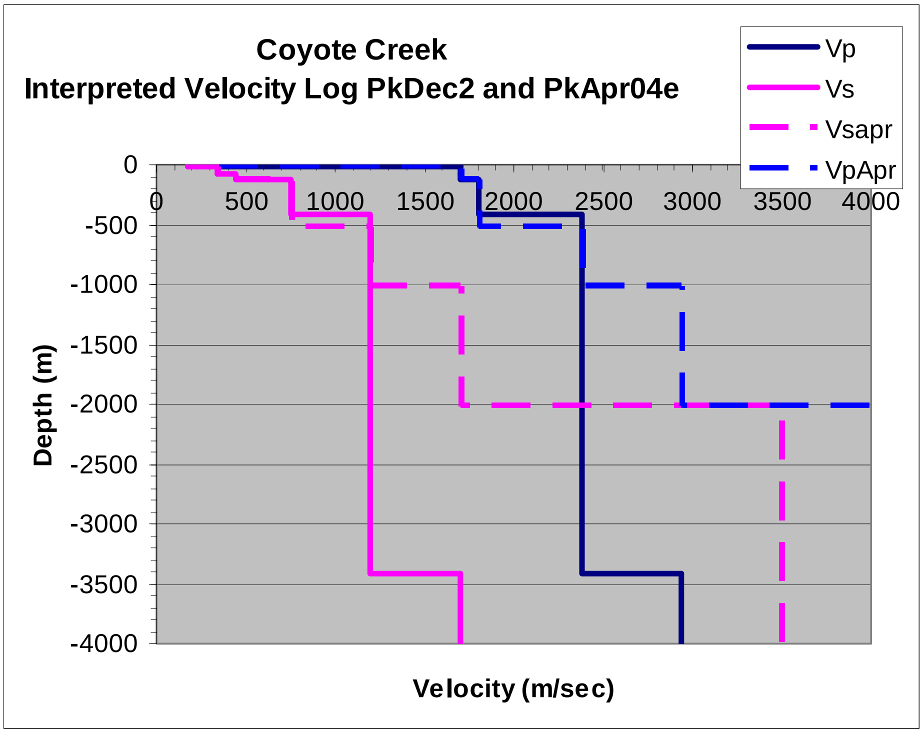


Fig. 2. Coyote Creek site: profiles of shear velocity (Vs) with depth interpreted from SPAC data in Fig.1. The profiles of Vp with depth are guesses, as Vp is generally not resolved by this method. Solid lines are model PkDEc2, interpreted “blind” with no geological or other independent data available.

Dashed lines are model PkApr05, re-interpreted to fit a known geological basement at depth order 1000 m.

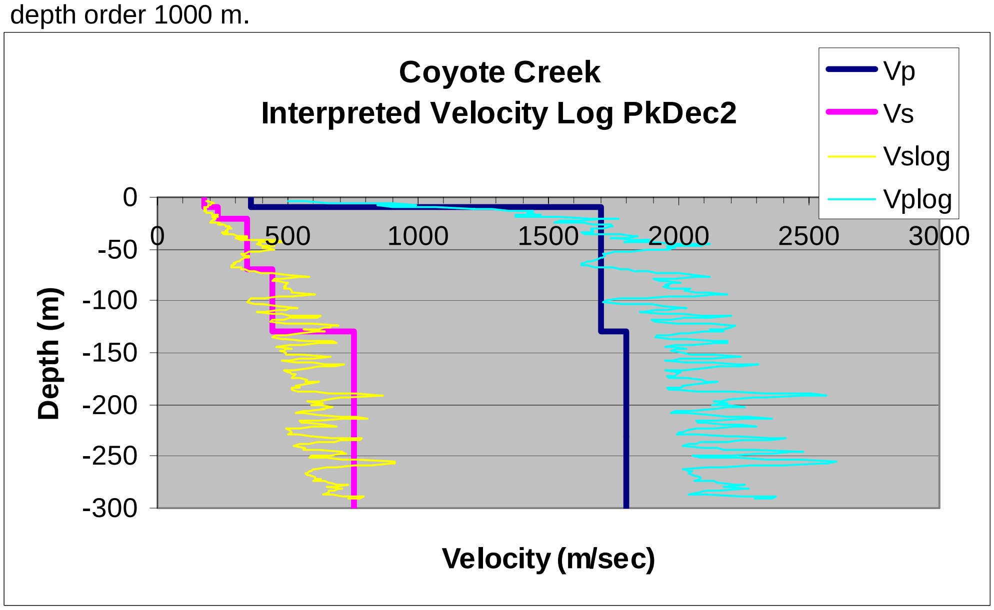
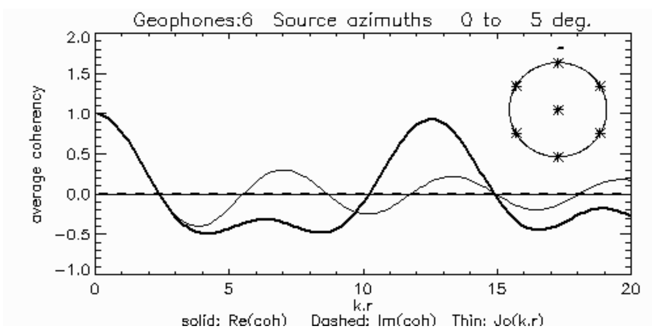


Fig. 3. RIGHT: Coyote Creek site: profile of shear velocity (Vs) with depth interpreted from SPAC data “blind” as in Fig. 2. Superimposed are independently measured borehole velocity logs acquired in the CCOC water bore.

Array design and microtremor data acquisition in the Santa Clara Valley

The MMSPAC method is optimized when SPAC data is acquired from a maximum number of inter-station separations. When using a seven-station nested-triangle array, SPAC spectra can be computed simultaneously for six different station separations (Asten et al, 2004). The optimum ratio of sizes for the two triangles has been derived to be a radius ratio of 3.5:1. This array design was used for acquisition of further data at water-bore sites Guadalupe, Santana Park, Saratoga Park and McGlincey in the Santa Clara Valley. As with Coyote Creek, interpretation at these sites is being performed "blind" and will be reported after borehole velocity data is made available for purposes of comparison.

A series of modeling studies has been conducted to investigate how limitations of finite array station numbers, and/or discrete directions of wave propagation affect the underlying assumptions in the spatial averaging of coherencies. Figure 4 shows an example which illustrates how the underlying assumption of a Bessel function shape for the SPAC curve is inadequate when the wave energy is highly directional. Further examples have been published in Asten (2003) and Asten et al (2004).



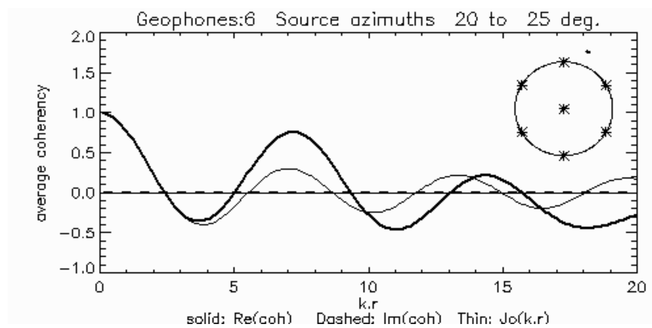


Fig. 4. Modelling SPAC with a hexagonal array and directional wavesalong a radius, and between two radii. The modelled SPAC curve (thick black line) is very different from the ideal bessel function (thin black line).

Prototype inversion software

Inversion to produce matching of SPAC spectra (which in general contain multiple maxima and minima, zero crossings, and with bias especially evident in higher coherency amplitudes) places different demands on curve fitting algorithms than does the process of matching dispersion curves (non-zero, positive and monotonically increasing values). Studies thus far demonstrate that a least-squares error criterion produces a valid local minimum when the initial model is close to a final model, but stability in the case of significant model mismatch remains a challenge.

The computed standard deviation over a selected frequency band shows sufficient sensitivity to derive bounds for estimated modeled layer velocities. Figure 5 shows results of a parameter sensitivity study on layer velocities for the Coyote site. Resolution of Vs is typically +-5% for the upper 100 m of soft sediments.

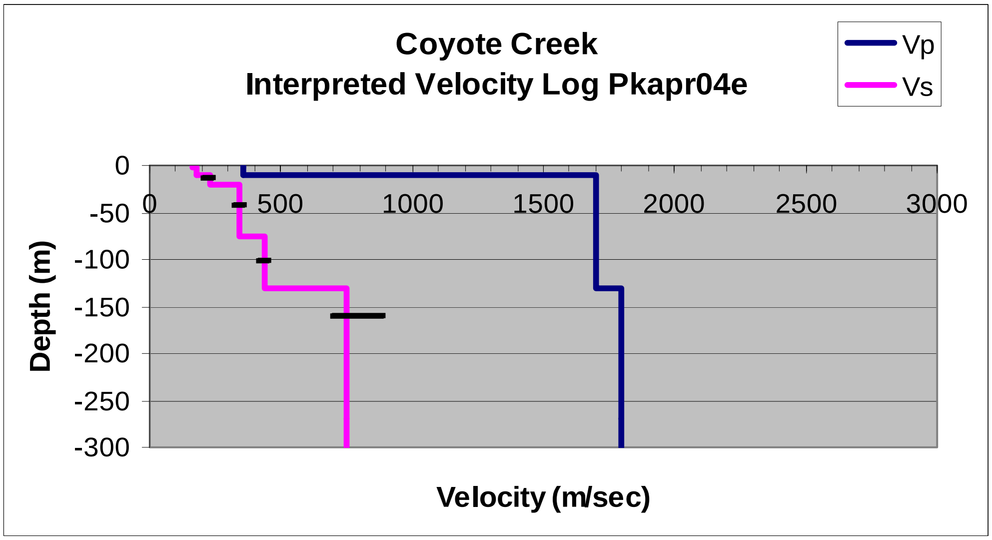


Fig. 5. RIGHT: Resolution of layer velocities (shown as horizontal black bars) estimated from studies of variation in standard deviation of fit of model and observed SPAC spectra with respect to perturbations in individual layer velocities. Resolution for this example is typically +- 5% for layers in the top 100 m, and +- 20% for the interval 150 to500 m.

NON-TECHNICAL SUMMARY

Characterization of the thickness and softness of geologically-young river and Bay-area sediments is a necessary part of earthquake hazard zonation. The techniques under development in this project measure natural earth vibrations called microtremors, caused by urban road traffic and machinery. By using arrays of seismometers placed for a few hours on suburban streets, sufficient data can be gained to interpret a softness versus depth profile to depths of up to 1 km, without using expensive drilling (typically $16,000 per hole) or active seismic surveys. Measurements at sites having detailed independent data provided by deep water bores proves the method to be effective.

REPORTS PUBLISHED

The instruments used in the field program were provided by the PASSCAL facility of the Incorporated Research Institutions for Seismology (IRIS) through the PASSCAL Instrument Center at New Mexico Tech. Data collected during this experiment is available through the IRIS Data Management Center. The facilities of the IRIS Consortium are supported by the National Science Foundation under Cooperative Agreement EAR-0004370.

A brief description of instruments used and data location and times is provided in the following:

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Archived data in SEED format is available from this website.

Related Papers published and Conference Presentations during 2003-4
* indicates peer reviewed papers

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